MASTER COPY: PLEASE KEEP THIS "MEMORANDUM OF TRANSMITTAL" BLANK FOR REPRODUCTION PURPOSES. WHEN REPORTS ARE GENERATED UNDER THE ARO SPONSORSHIP, FORWARD A COMPLETED COPY OF THIS FORM WITH EACH REPORT SHIPMENT TO THE ARO. THIS WILL ASSURE PROPER IDENTIFICATION. NOT TO BE USED FOR INTERIM PROGRESS REPORTS; SEE PAGE 2 FOR INTERIM PROGRESS REPORT INSTRUCTIONS.

MEMORANDUM OF TRANSMITTAL

U.S. Army Research Office
ATTN: AMSRL-RO-BI (TR)
P.O. Box 12211
Research Triangle Park, NC 27709-2211

☐ Reprint (Orig + 2 copies)

☐ Technical Report (Orig + 2 copies)

☐ Manuscript (1 copy)

☒ Final Progress Report (Orig + 2 copies)

☐ Related Materials, Abstracts, Theses (1 copy)

CONTRACT/GRANT NUMBER: DAAD19-00-1-0007

REPORT TITLE: Heterostructure Field Effect Transistors Fabricated from Germanium-alloyed Silicon Carbide

is forwarded for your information.

SUBMITTED FOR PUBLICATION TO (applicable only if report is manuscript):

Sincerely,

James Kolodzey

20010416 041

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)

2. REPORT DATE 29 March 2001

3. REPORT TYPE AND DATES COVERED
12/06/99-12/05/00 FINAL

4. TITLE AND SUBTITLE
Heterostructure Field Effect Transistors
Fabricated from Germanium-alloyed Silicon Carbide

5. FUNDING NUMBERS
DAAD19-00-1-0007

6. AUTHOR(S)
James Kolodzey

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Department of Electrical and Computer Engineering
University of Delaware
Newark, DE 19716

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

ARO 40352.1-EL

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

For high power, high voltage applications, SiC would be more versatile if suitable heterojunction partners were available. Using ion implantation, we formed alloys of SiC with a few atomic percent of Ge. The Ge was implanted at 300 KeV and a dose of 1.67×10^{16} cm^{-2} into p-type, 4H-SiC, wafers. The wafers were annealed at temperatures up to 1700°C. Raman Spectroscopy confirmed that the 4H structure was reconstructed after annealing. X-ray diffraction (XRD) Rutherford Backscattering spectrometry (RBS) showed an increase in the lattice constant, implying that some of the Ge was substitutional, and that the amount of substitutional Ge increased with annealing. Electrical conductivity showed only small changes, suggesting that the Ge is not a dopant, and does not significantly change the mobility. SiC:Ge/SiC heterojunction devices were formed using Ti/Au as an electrical contact. Current-voltage (I-V) and capacitance measurements confirmed a reduction of the built-in voltage compared to similar SiC devices without Ge. The heterojunction forward current was found to behave as exp(qV/nkT), where the ideality factor (n) was 2. These results indicate that the SiC:Ge/SiC is promising for device applications.

14. SUBJECT TERMS
Silicon carbide materials and devices, SiC alloys with germanium, high power devices

15. NUMBER OF PAGES
9

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

For the implantation of Ge atoms, the 4H SiC substrate was lightly p-doped, and it was approximately 420 um thick from Cree Research . A section of approximately half of the wafer was implanted with nitrogen (N) to generate a highly doped surface n-type region having a peak doping concentration of 1×10^{20} cm^{-3}. After rotating the wafer by 90°, it was again implanted with Ge to approximately 8×10^{20} cm^{-3} from a 300 KeV ion beam source having a dose of 1.67×10^{16} cm^{-2}. This resulted in a wafer with quadrants of surface layers of SiC:Ge, with and without nitrogen on the surface of the original SiC substrate. The goal of the study was to determine the effects of Ge on the properties of p and n type SiC for possible use in SiC/SiCGe heterostructure device applications. The substrate was subsequently annealed in a rapid thermal annealer to a maximum temperature of 1700 °C. Measurements included Rutherford backscattering spectroscopy (RBS), x-ray diffraction (XRD), optical absorption, and electrical measurements (I-V and C-V). Earlier research with Ge implanted 4H-SiC demonstrated the ability to implant Ge atoms substitutionally into the SiC lattice with thermal stability of the SiC:Ge thin layer to 1000 °C. These earlier layers contained 1.4% Ge and they had an increased lattice constant compared to the original 4H-SiC.[1] The research reported here provides new data with evidence of thermally stable implanted SiC:Ge having increased lattice constants and lower forward voltage drops in the devices, compared to unalloyed SiC.

The RBS data was obtained with a 2 MeV He+ ion accelerator. This was used for both the SiC and the SiC:Ge regions of the substrate. The data was compared to theoretical calculations using the Rutherford universal manipulation program (RUMP). We found that the RBS data for the SiC:Ge layer (Fig. 1), indicates regions attributed to the underlying SiC substrate, the SiC:Ge surface layer, and a thin region of Ti metallization on the surface. The RUMP simulations yield a SiC:Ge layer thickness of 2700 A with a total peak concentration of 1.6% Ge atoms in the layer.

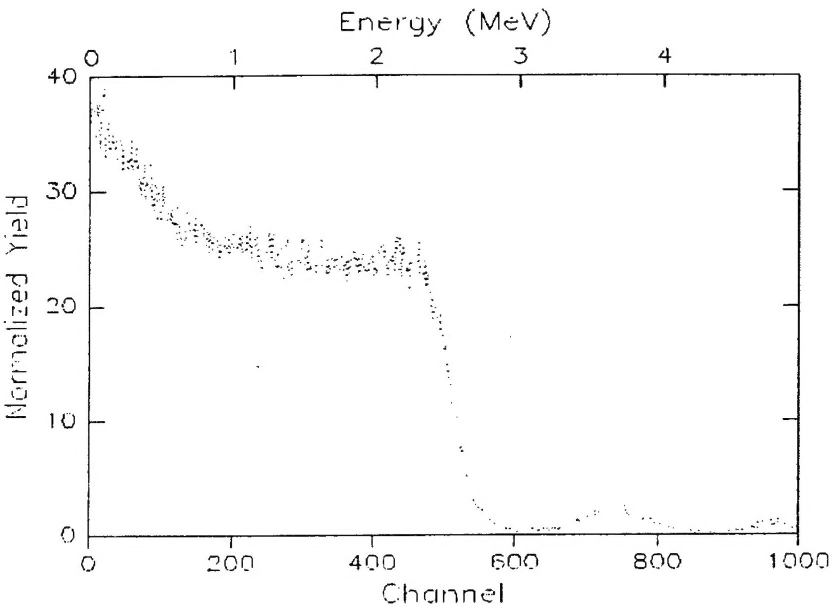

Figure 1. RBS data from the SiC:Ge layer showing evidence of C, Si, and Ge profiles.

X-ray diffraction was used to characterize the SiC:Ge crystalline structure including the Ge concentration and the SiC:Ge lattice spacing relative to that of the SiC substrate. Measurements were performed on a Philips X-pert diffractometer utilizing the $Cu_{K\alpha}$ wavelength in the symmetrical Bragg configuration at low resolution. The results of the XRD measurements for the SiC substrate compared to that of the SiC:Ge region are given in Fig. 2. The XRD data for the 4H SiC substrate is typical of that observed in previous studies with a sharp peak at about 35.7 degrees, which corresponds to the 0004 plane. The Ge implanted SiC sample has a contribution that is centered around 35.2 degrees, which indicates an increase in the SiC lattice constant and is attributable to the substitutional Ge. Samples were implanted with varying amounts

of Ge doses for the purpose of determining the relative X-ray diffraction measurements as a function of Ge content. The three curves in Fig. 3 represent Ge ion implantation doses of, 1 x 10+15 cm-2 (sample d), 2 x 10+16 cm-2 (sample c), and 8 x 10+16 cm-2 (sample e). Compared to the unimplanted SiC, samples c, d, and e, have an increasing amount of X-ray intensity near 35.2 degrees, resulting in a distorted or asymmetrical "shifting" of intensity toward slightly lower Bragg angles. The largest secondary peak is from sample e, which had the highest Ge dose during implantation. The X-ray intensity for Bragg angles just greater than the 4H SiC peak at 35.5 degrees increased monotonically with the Ge implantation dose. This increase, however, is attributed to lattice damage from the implantation process. More data will be required to understand the effects of implant damage, however.

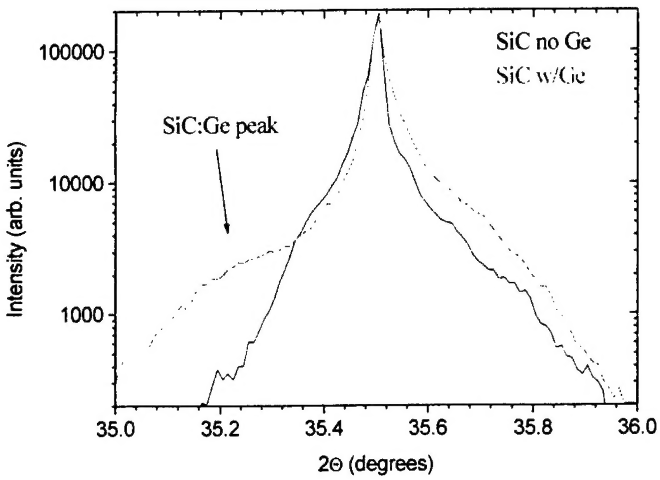

Figure 2. X-ray diffraction data from SiC and Ge implanted SiC substrates. The data from the SiC:Ge sample is observed to have a Bragg reflection peak centered near 35.2 degrees, while the 0004 plane of the SiC substrate is evident near 35.5 degrees.

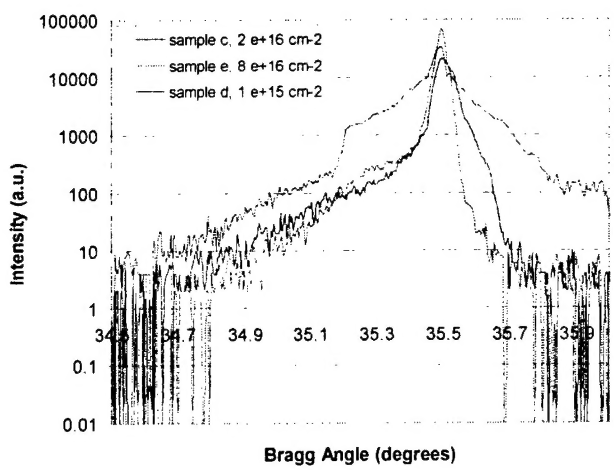

Figure 3. X-ray diffraction data of three samples of SiC with varying amounts of Ge doses during implantation.

Metal contacts were formed on the SiC/SiC:Ge wafer by e-beam evaporation of Ti/Au directly onto the front and backside with an evaporation chamber pressure of approximately 1 x 10-7 Torr. The contacts were subsequently annealed in a rapid thermal annealer (RTA) to 800°C in forming gas. Devices were formed having circle top contacts with the backside of the sample as a large area back contact. The current-voltage (I-V) measurements were performed using a Hewlett Packard 4156B Parameter Analyzer. I-V data was taken

before and after contact annealing were compared. Fig. 4 shows the I-V data of the four regions of the wafer *before* contact anneals. Note the highly symmetric I-V for the SiC case, as expected for a homogeneous bulk SiC layer. For the other three cases, asymmetry implies some rectification and/or diode action as expected with implant/doping. Fig. 5 shows the I-V data *after annealing* of the same four regions as in Fig. 4. In all sections the total current increased after annealing especially for the section implanted with just Ge (section 2). The presence of Ge and the dopant N yielded much higher currents than for the unimplanted diodes. Breakdown voltages (not shown) for the diodes exceeded the range of the instrument (-50 V).

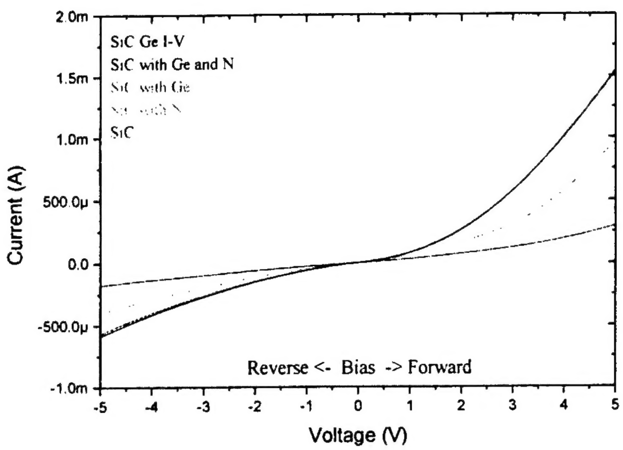

Figure 4. Electrical (I-V) measurements of SiC, n-type SiC, SiC:Ge, and n-type SiC:Ge, prior to thermal annealing of the metal contacts.

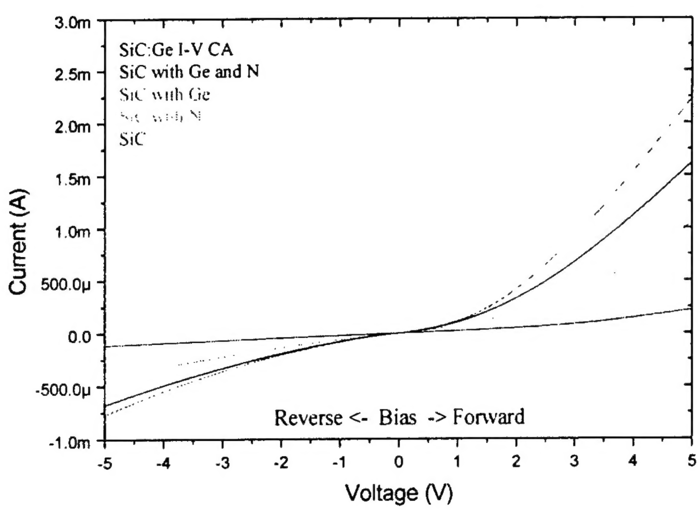

Figure 5. Electrical (I-V) measurements of SiC, n-type SiC, SiC:Ge, and n-type SiC:Ge, after thermal annealing of the metal contacts.

Capacitance-Voltage measurements were performed on the heterostructure diodes to extract the built-in voltage, Φ_{bi}. Plots of $1/C^2$ versus voltage are shown in Fig. 6. The incorporation of the dopant N increases Φ_{bi}, as one would expect from the difference in E_F between the two layers. The incorporation of Ge decreases Φ_{bi}, as expected, since the bandgap of Ge (0.66 eV) is much smaller than 4H SiC (3.2 eV). The addition of just Ge to SiC caused a 40 mV decrease in the built-in voltage, which is in reasonable agreement with optical absorption spectroscopy measurements that were taken.

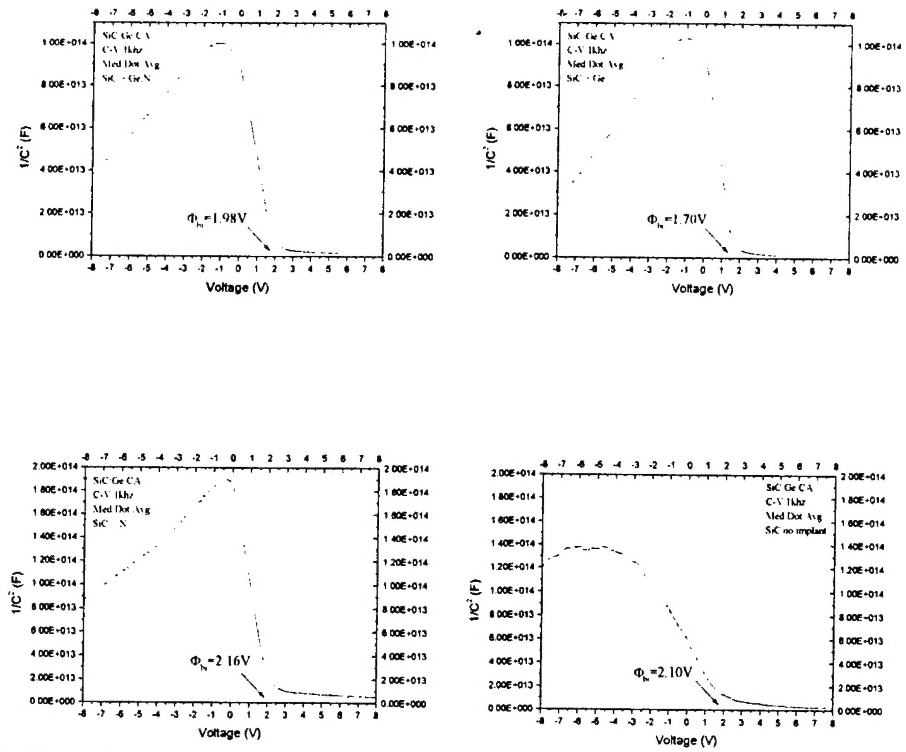

Figure 6. Capacitance-Voltage measurements made of SiC, n-type SiC, SiC:Ge, and n-type SiC:Ge showing varying built in voltages and a minimum value of built in voltage for the SiC:Ge sample.

Electrical contact experiments were carried out to determine how Ge affects the electrical contacts for a p-type SiC wafer. the affect of Ge implantation the properties of the electrical contacts for a p-type SiC wafer. Other researchers have demonstrated the ability to develop reliable electrical contacts with CrB alloys on p-type SiC wafers.[2] Our approach was to evaporate a thin layer of Cr followed by a thicker layer of Ni onto both a SiC wafer (p-type without Ge), as a reference, and a Ge implanted wafer for comparing the experimental I-V data between the two. The preliminary measurements of both structures in Fig. 7 show the "as deposited" I-V data of both samples prior to thermal annealing. The electrical contacts of both samples were fabricated by thermal evaporation with a pressure of approximately 1 x 10-7 Torr by first depositing a thin 500 A layer of Cr and then 1000 A of Ni. The I-V data were taken with a Cascade DC probe station and a HP 4156B Semiconductor Parameter Analyzer. The data for the SiC and the SiC:Ge sample are greatly different. For the SiC:Ge sample the current voltage relation is linear, whereas the I-V characteristic of the SiC contact is nonlinear and suggests a rectifying semiconductor junction having a breakdown voltage of approximately 4.2 volts. The contact resistance of the metallization on the SiC:Ge wafer is lower than that of the SiC contact resistance with the same metallization structure, as noted by the current which is two orders of magnitude larger compared to that of the SiC measurement. The SiC:Ge sample is p-type with Al to 3 x 10^{+18} cm-3 and implanted with a Ge dose of 8 x 10+16 cm-2. Further experiments including RBS will be needed to characterize the effects of Ge implantation on the quality of unannealed electrical contacts made from CrNi on p-type SiC.

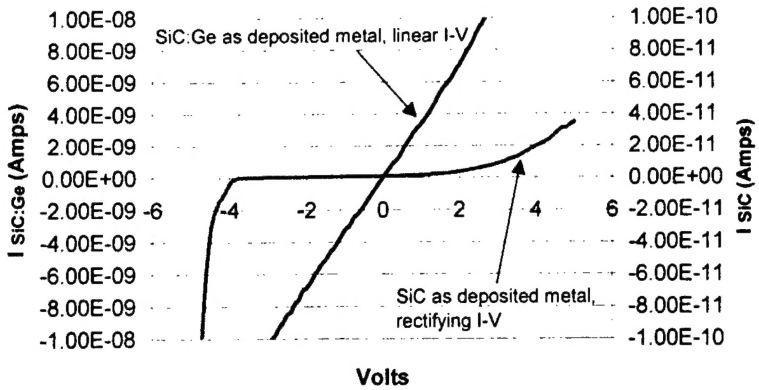

Figure 7. Electrical (I-V) data of SiC and SiC:Ge metal contacts fabricated from Cr/Ni which show an Ohmic contact for the SiC:Ge case and a rectifying contact for the SiC case.

The effect of Ge ion implantation on the physical properties of silicon carbide substrates has been investigated experimentally to determine possible utilization of the material in heterostructure electronic device applications. The results of the study of a p-type 4H SiC substrate implanted with Ge from a 300 KeV ion beam indicate the formation of thin layers of SiC:Ge with approximately 2% Ge concentration. Annealing experiments up to 1700 °C showed that the 270 nm layer has a lattice constant that is larger than the SiC substrate used in the study. The X-ray diffraction data of the SiC:Ge layer resulted in an significant X-ray peak near 35.2 degrees compared to the SiC 0004 peak at 35.7 degrees, which implies a Ge content of 2.37% when Vegard's linear law is assumed. This data is in reasonable agreement with RUMP predictions of 1.6% Ge that was fitted to experimental RBS data of the SiCGe sample. I-V measurements have shown that heterojunction SiC/SiC:Ge devices have a lower forward voltage drop to either SiC or N-doped SiC devices. C-V data indicates a lowering of the built in voltage by 40 meV for Ge implanted SiC. Finally, Cr/Ni electrical contacts have been fabricated onto Ge implanted SiC substrates and they have been observed to achieve Ohmic contact characteristics with linear, non-rectifying behavior when evaporated directly onto the SiC:Ge layers and prior to annealing.

REFERENCES

1. G. Katulka, C. Guedj, J. Kolodzey, R.G. Wilson, C. Swann, M.W. Tsao, J. Rabolt, Applied Physics Letters, 74, 4 (1999)
2. T.N. Oder, J.R. Williams, M.J. Bozack, V. Iyer, S.E. Mohney, and J. Crofton. Journal of Electronic Materials, Vol. 27, No. 4, 1998.